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DESIGN, FABRICATION AND TEST OF A 4750 NEWTON-METER-SECOND DOUBLE GIMBAL CONTROL MOMENT GRYOSCOPE

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ABSTRACT

In recognizing the need to develop future technologies in support of the space station, NASA's Advanced Development Program (ADP) placed as its goal the design and fabrication of a prototype 4750 N-m-sec (3500 ft-lb-sec) Control Moment Gyroscope (CMG). The CMG uses the principle of momentum exchange to impart control torques to counteract vehicle disturbances. This paper examines the selection of the double gimbal over the single gimbal CMG and describes the major subassemblies of the selected device. Particular attention is given to how the man-rated mission requirement influenced the choice of the materials, fabrication, and design details employed.

Physical characteristics and the results of functional testing are presented to demonstrate the level of system performance obtained. Comparisons are made of the measured system responses against the predictions generated by computer simulation.

INTRODUCTION AND HISTORY

NASA initiated the ADP in parallel with the Phase B definition and preliminary design efforts for the space station. The purpose of this program was to focus on technologies applicable to the initial space station with the goal of accelerating these technologies to meet the proposed operational schedule for the station. Other objectives of the ADP were to enhance the performance of the space station, reduce life cycle cost during the operations phase, and reduce risks encountered during the development phase.

The Attitude Control Stabilization (ACS) team of the ADP proposed a number of technical activities, one of which was the design, fabrication, and test of a prototype CMG. Using a CMG for control of the Space Station Freedom seemed obvious since a CMG has a replenishable momentum capability, which is achieved through appropriate gravity gradient desaturation maneuvers and requires no consumables. NASA's experience with this type of control was amply demonstrated on the Skylab program in the mid-seventies. Skylab used three double-gimbal CMGs (DGCMGs) for attitude control, and employed gravity gradient maneuvers and a thruster system for momentum bias desaturation.

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The first decision to be faced by the ACS team was whether to develop a DGCMG or a single gimbal CMG (SGCMG) for the space station prototype.

The advantages of DGCMGs include:

- Much simpler control laws without elaborate singularity avoidance
- No impact of unit failure on control laws
- No impact of failure on spherical momentum envelope shape
- Growth capability by adding individual DGCMGs without impacting control laws
- Simpler vehicle mounting geometry.

SGCMGs have an advantage in that they can provide greater torque capability for the same angular momentum. Since the Space Station Freedom has no rapid maneuvering requirements necessitating high torques, this did not prove to be an important consideration for this application.

System-level trade studies involving weight, size, power, and reliability produced no advantage to either type, since the SGCMGs require oversizing to produce the same angular momentum envelope as DGCMGs. The flexibility of the DGCMG to support a large variation in vehicle inertia, especially during station build-up, ultimately proved to be the main consideration for the selection. Since the ACS control laws are not affected by the number of units employed, the initial manifest need not contain the full complement of units. As the station assembly configuration changes, additional CMGs could be added at any time to support the ACS requirements.

The prototype CMG design parameters were extrapolated from the Skylab CMG experience, and improvements were made in a number of areas based primarily on the momentum storage capability and the long life required for the Space Station Freedom application. Marshall Space Flight Center (MSFC) was selected to lead the CMG development effort, since that center had been responsible for the Skylab CMG development and had the technical expertise and testing capability for continued CMG development. Subsequently, MSFC selected the Guidance Systems Division (GSD) of the Allied-Signal Aerospace Company (formerly The Bendix Corporation) to design, develop, and fabricate a prototype CMG under NASA contract NAS8-36628. The final concept is a double gimballed system with unlimited freedom for the outer gimbal and a 50-percent increase in angular momentum from the Skylab CMG. Mechanical features incorporated are an on-orbit servicing capability, power and signal transfer through rotary transformers and fiber optics respectively, and an active oil lubrication system for the spin bearings. The three-year development has resulted in a prototype CMG which will undergo verification and life testing at MSFC.

System Requirements

The CMG was designed to meet the following minimum system requirements:

- Angular momentum to be 4750 N-m-sec (3500 ft-lb-sec) at a speed of 6600 rpm
- Peak output torque applied to the space station shall be equal to or greater than 274 N-m (200 ft-lbs) for the maximum coupling condition with a maximum gimbal rate of 0.057 rad/sec (3.27 deg/sec)
- Outer gimbal to provide unlimited angular freedom
- Inner gimbal to provide ± 1.57 rad (90 deg) angular freedom
- Rotor design to have a safety factor of 4 on yield stress
- CMG design goal to insure reliability and a 10-year operational life.

CMG Configuration Trade Studies

A trade study was performed to optimize the selection of the rotor material. The study compared a wide range of candidate materials for the following mechanical properties:

- Material strength
- Fracture toughness
- Stress corrosion resistance (MSFC-SPEC-522B)
- Producibility.

In addition to the above parameters, the following constraints were also considered:

- Rotor diameter of 63 cm (25 in.)
- Rotor speed less than 9000 rpm
- No maraging steel
- Use of materials with published data base.

In order to make comparisons between various materials, three candidate systems were established and analyzed. Each of the designs was analyzed for weight, inertia, momentum, and yield stress. In addition, rotor stiffness and resonant frequencies were examined for each case. The conclusion of this study led to the selection of Custom 455 stainless steel as the optimum rotor material.

A second trade study was performed to determine the feasibility of replacing CMG rotor bearings during the mission. The long duration mission proposed for the space station program requires that the CMG rotor spin bearings must perform consistently for a minimum of 10 years. Even with a theoretical reliability of 0.999, the possibilty of bearing deterioration or failure exists. Typically, degradation in bearing performance is characterized primarily by an increase in average friction torque with a corresponding increase in motor power consumption. In the case of serious bearing degradation, a bearing replacement would prevent loss of the CMG and its corresponding impact on the mission. As a result of the trade study, a bearing configuration has been incorporated into the CMG rotor bearing design which could support replacement of the bearings on-orbit if deterioration is detected.

Repairability and ORU Design Concept

The prototype CMG was designed using the orbital replaceable unit (ORU) concept to make repairs and component replacement in space as convenient as possible. For CMG removal, the mounting pads were designed for captive bolts, which prevent bolt loss after removal. Sufficient clearance exists between electrical connectors to allow insertion or removal by an astronaut wearing a space suit. The CMG is provided with handles to allow relative ease of on-orbit handling.

Electronic assemblies can be replaced without disturbing the mounting of the CMG. However, for safety considerations, it is recommended to remove power from the CMG prior to this replacement. Captive bolts and quick disconnects will facilitate the replacement of the ORUs.

Spin bearing replacement was designed to be achieved after placement of the CMG into a space station "shirt-sleeve" work area. The actual replacement procedure requires some mechanical acumen and extensive training to become familiar with the unit, tooling, and assembly sequence.

DESIGN DESCRIPTION

The design of the CMG is an evolution based on many CMG and momentum exchange devices built and flown since the Skylab program. Most of the major components of the system have a successful heritage and design base in keeping with the man-rated mission requirements of the Space Station Freedom. The system shown in Figure 1 consists of a rotor mounted within two sets of orthogonal gimbals so as to orient the spin axis of the rotor in any desired direction. All the drive and support electronics are mounted on the mounting ring and gimbal structures to minimize signal transfer across the gimbal pivots.

A simplified block diagram of the system is presented in Figure 2. The Outer Gimbal Electronics Assembly (OGEA) accepts the external electrical interface in the form of power and a MIL-STD-1553 serial communications link. In the OGEA a microprocessor channels the communication of command and telemetry signals, and thus requires no analog signal processing of any type. Power is transferred across the outer gimbal pivot using redundant rotary power transformers. Communication between the OGEA and Inner Gimbal Electronics Assembly (IGEA) is performed via a Fiber Optic Rotary Joint (FORJ). In this manner no contacting signal transfer is employed where life limitations might be of concern.

The Rotor Electronics Assembly (REA) controls and monitors the speed of the rotor and is mounted on the inner gimbal. Signal transfer is accomplished from the IGEA to the REA by a limited-motion twist capsule, which is protected by gimbal stops that limit the inner gimbal motion to 90 deg. The major electrical functions are cross-strapped to improve overall system reliability and minimize the orbital replacement operation.

The major interface characteristics are described below:

- Size:
  - Length: 1.21 m (47.8 in.)
  - Width: 1.16 m (45.9 in.)
  - Height: 1.15 m (45.5 in.) - With outer cover in place
- Weight: 279 kg (615 lb)
- Mounting: 4 Point C.G. (Gimbal axes lie in the mounting plane)
- Power: (120 Vdc)
  - Quiescent: 95 W
  - Spin-Up (Peak): 240 W

The following sections will describe in further detail the major components of the system and what requirements influenced the design or fabrication activities.

Rotor Design and Safety Analysis

A cross-section of the rotor installed in the Inner Gimbal Assembly (IGA) is presented in Figure 3. The rotor is a single-web wheel forged from Custom 455 stainless steel. It is supported at each end by a single angular contact ball bearing. Outside diameter of the rim is 0.635 m (25.0 in.) and the overall shaft length is 35 cm (13.85 in.). Custom 455 is a precipitation hardenable steel and is considered highly resistant to stress corrosion cracking. Extensive testing was performed by GSD to properly qualify this material and verify the physical and mechanical properties.

A finite element model of the rotor was created and analyzed for stresses and deflections using NASTRAN. The centrifugal loading of the rotor at 6600 rpm produces the maximum steady operational forces. Gyroscopic stresses on the rotor are of much less concern due to the low level of output torque that is required of the system. A modified Goodman diagram presented in Figure 4 illustrates that the combined centrifugal (steady) and gyroscopic torquing (cyclic) stresses are well within the infinite life region of the graph.

A design requirement was placed on the rotor to provide a factor of safety of four on yield stress at 105 percent of the nominal wheel speed (6930 rpm). An analysis of the rotor stress results in a peak value in the web of 296 MPascals (43 kpsi). Comparing this to the 1.2 GPascals (175 kpsi) yield strength of the material produces a safety factor greater than required. During component test, the rotor was subjected to an overspeed of 1.33 times the nominal speed (8800 rpm), and survived.

Spin Bearings and Lubrication System

The spin bearings used in the design are angular contact type 107H size ball bearings with special retainers. This configuration has been used previously and dates back to the Skylab CMG. The bearing retainers have been modified to provide proper distribution of the lubricant to the ball and race contact zone. The material for the races and balls is VIM-VAR 52100 chrome steel, and the retainer is fabricated from a cotton-based phenolic impregnated with bearing lubricant.

When assembled, the bearings are preloaded by a constant force Belleville spring that ensures the bearings remain preloaded under all conditions. Low-level heaters are provided in the housing for low temperature operation if required.

To support the 10-year life requirement, an active lubrication system was chosen. This system will provide a flow of new KG-80 lubricant in a "one-time-through" manner to continually lubricate the bearing over the design life of the CMG. The reliability of the bearing is enhanced by this system and is far superior to grease lubrication for long mission durations.

Torque Motor and Transmission

To develop the required torque of 272 N-m (200 ft-lb), a torque motor and geared transmission are utilized. The motor is a brushless DC type design capable of developing 12 N-m (9 ft-lb) or torque. An ironless stator is employed which produces no hysteresis or eddy current losses, and thus eliminates magnetic cogging and drag torques for better system performance.

The gear train employed in the transmission is shown in Figure 5 and consists of a two-stage, parallel-path spur gear arrangement. Windup of one gear train path with respect to the other provides a preload that effectively eliminates backlash in the transmission. A gear ratio of 27.76 to 1 allows the motor to achieve the required torque level. This type of configuration has been employed on previous designs, including a unit that has accumulated six years of special life testing under severe duty cycle operations.

These components are housed in the Torquer Module Assembly (TMA), along with a multi-speed resolver used for rate feedback. Shown in cross-section in

Figure 6, this assembly is identical for both the inner and outer gimbal pivots.

Gimbal Drive Electronics

Both the inner and outer gimbals are rate controlled in a closed loop manner using a phase-locked-loop technique. This technique permits high input command resolution and precise rate control without the necessity for precision low-signal-level analog electronics. In operation, the 16-bit digital rate command is applied to a digital low-pass filter, the output of which is accepted by a Binary Rate Multiplier (BRM). The BRM acts as a digital number-to-frequency converter.

A 16-speed resolver acts as a rate sensor and produces an output whose frequency is proportional to the gimbal speed. The resolver and BRM outputs are applied to a phase detector which produces an output proportional to the phase difference between the two input frequencies. The phase detector output is then applied to a compensation network needed for loop stability, and a notch filter to attenuate phase detector carrier harmonics. This signal is then applied to a power amplifier which contains a multiplier unit to achieve commutation for the torque motor. A current feedback technique is utilized by the amplifiers to produce a current-source drive. In response, the motor accelerates to a speed which causes the resolved output frequency to come into exact correspondence with the command frequency.

Rotor Drive Electronics

The rotor drive is also controlled by a phase-locked-loop design. Nominal wheel speed is defined as 6600 rpm, but the system is capable of being commanded to operate at 5 percent above and below this value. A frequency is generated by a Hall resolver and compared to the commanded reference frequency. The difference in these two signals generates an error signal that is applied to a phase detector, amplified, and frequency shaped. It is then applied to the PWM current amplifier which is commutated by the output of the Hall resolver. A current feedback technique is utilized by the amplifiers to produce a current source-drive to the spin motor.

MATHEMATICAL MODELING

For design and analysis purposes, the behavior of the CMG can be characterized by a 6-mass model. This model represents both the inner and outer gimbal loops which are coupled as a function of the inner gimbal angle. In general, the loops are designed as high-gain wide-bandwidth rate loops to enhance small signal performance and damp the gear train resonance. A digital prefilter is used to provide the overall bandwidth characteristics as viewed by the vehicle control loops. When the proper stabilization networks are employed, the inner gimbal loop produces the frequency response characteristics shown in Figure 7.

From this linear model, a nonlinear representation was developed that permits a more accurate determination of CMG performance. A simulation was generated using the Boeing Computer Services EASY-5 Analysis Program, and incorporates nonlinear effects such as: torque motor saturation, gear train compliance, electronic limits, and pivot friction. The model can be exercised for any type of input command (i.e., sinusoidal, step, impulse, or impulse train).

TEST RESULTS

Support Equipment

The CMG system is supported during testing by an automated computer-controlled test station. Interface to each of the two channels of the CMG is via a single cable, which supplies power and provides a dual redundant serial data link. The station uses an IBM PC/AT computer equipped with a 30-Mbyte hard disk drive. All operator interface and monitoring of the CMG is provided by a MIL-STD-1553 serial communications bus which plugs directly into the computer. Power requirements to the system are provided by a 120-Vdc supply that is controlled and monitored by the test station computer.

The computer displays the command status and health of the system on a CRT monitor. Response data from the unit is processed and various flags, alarms, and shutdowns are automatically implemented by the station. Hard copy of the display may be obtained on command or at regular intervals. Test data can be stored or transferred to floppy disk for post processing.

Force and Moment Table

To measure output performance, a force and moment table was designed and built for the CMG system. This table uses four piezoelectric three-axis force sensors, whose outputs are summed according to their mounting geometry to produce the three forces and moments that completely describe the system mechanical output. Using a digital signal analyzer, these signals can be displayed in either the time or frequency domain to characterize the output performance levels as described in the following paragraphs.

Frequency and Step Response

Figure 8 shows the results obtained for the frequency response test of the inner gimbal loop. This is typical of results obtained for both loops and demonstrates the dependency on the inner gimbal angle. In general, the agreement is excellent when compared with the predicted results given earlier, although the test data has slightly more peaking. This effect was also noticed in the step response behavior of the system in both the overshoot and settling characteristics observed. This difference has been attributed to the gear train stiffness being lower than anticipated.

Gimbal Rate Linearity

Gimbal loop scale factor and linearity were measured for various commanded rates. The test consisted of commanding a constant rate for a known period of time and computing the actual rate from the change in gimbal angle. Figure 9 presents a plot of the difference between the measured rate and linear fit of the data. The results are typical for both loops and yield a linearity in the 0.1-percent range. Due to the manner in which the test was performed, these results represent errors in the test method employed rather than the system accuracy. This is consistent with the expected performance for the phase-locked-loop implementation as well as the commanded zero rate drift, which is below the threshold of what could be measured.

Torque Noise

Torque noise is defined as the undesirable component of torque produced by the actuator when a constant rate is commanded. Expressed in terms of the RMS components produced in the frequency domain, a measurement of this noise is given in Figure 10 for a 5.7 mrad/sec (0.327 deg/sec) commanded rate. Major contributors to this error source have been identified as the dc offset in the drive voltages and the transmission gearing. This plot is typical of both the inner and outer gimbal loops, and incorporates special balancing circuits to minimize the effect of the offset of the drive voltages. Total noise when viewed in the time domain produces a value of approximately 2-percent RMS for the case given.

Induced Vibration

Another performance parameter important to the operation of the space station is the induced vibration of the CMGs. Concerns exist for potential coupling to the inertial sensors, located on the same pallet, as well as the effect produced on the station micro-gravity environment. The dominant contributor to this performance is the balance of the rotor wheel as it rotates at the nominal speed of 6600 rpm. A full characterization of the system would consist of the three forces and moments that would be seen at the mounting interface for a host of gimbal positions. Typical values for these parameters have been measured, and result in forces that range from 0.45 to 2.2 N (0.1 to 0.5 lbs) and moments that range from 0.68 to 0.27 N-m (0.5 to 0.2 ft-lbs).

Gimbal Angle Readout

A readout of the gimbal positions is provided as a system output to provide necessary information to the momentum management and vehicle control laws. Measurements of the readout accuracies of both gimbals were below 1.7 mrad (0.1 deg) for all cases measured.

Wheel Speed Control

During all operations of the CMG, the wheel speed was monitored and the performance of the loop has exceeded the design goal of 0.1 percent. Actual speed never exceeds 2 rpm from the commanded value even during maximum rate conditions.

CONCLUSIONS

The development of the prototype DGCMG has provided NASA with a working design that meets or exceeds the goals of the Advanced Development Program. In addition to providing a safe design for man-rated missions, this device can contribute to the Attitude Control System definition and address concerns at a relatively early stage in the space station development. Major accomplishments of the program include the following:

- Successful demonstration of compliance to all the system requirements and design constraints imposed
- Concurrence of analytical models and simulation results to the measured performance
- Development of the necessary test station and the measurement equipment needed to characterize output performance.

PROPOSED FUTURE TESTS

The results obtained to date represent the current state of the system characterization. Future work is planned to improve the response and evaluate other performance parameters.

Cross-compensation

At present, cross-coupling between the inner and outer gimbal servo loops causes variations in the frequency response as a function of the inner gimbal angle. Although these bandwidth variations appear to be acceptable for the accuracy requirements of space station, a proposed improvement is to use a variable cross-feed compensation. The expected results would produce a frequency response characteristic nearly independent of inner gimbal angle.

Small Signal Characterization

Results for relatively large signal performance have previously been shown to agree with the linear model of the system. Small signal rate commands will be used to determine the effect of non-linearities such as dead-zone, if any exists, and gimbal friction. If required, these test results could then be used to modify both the model itself and the values assumed. The result would be a high-fidelity model that could be used to assist analyses and simulations of the ACS.

Life Tests

Current plans call for verification and life testing at MSFC. The support test equipment has been designed to simulate the duty cycle commands expected for Freedom, and thus provide a means to address the design life performance.

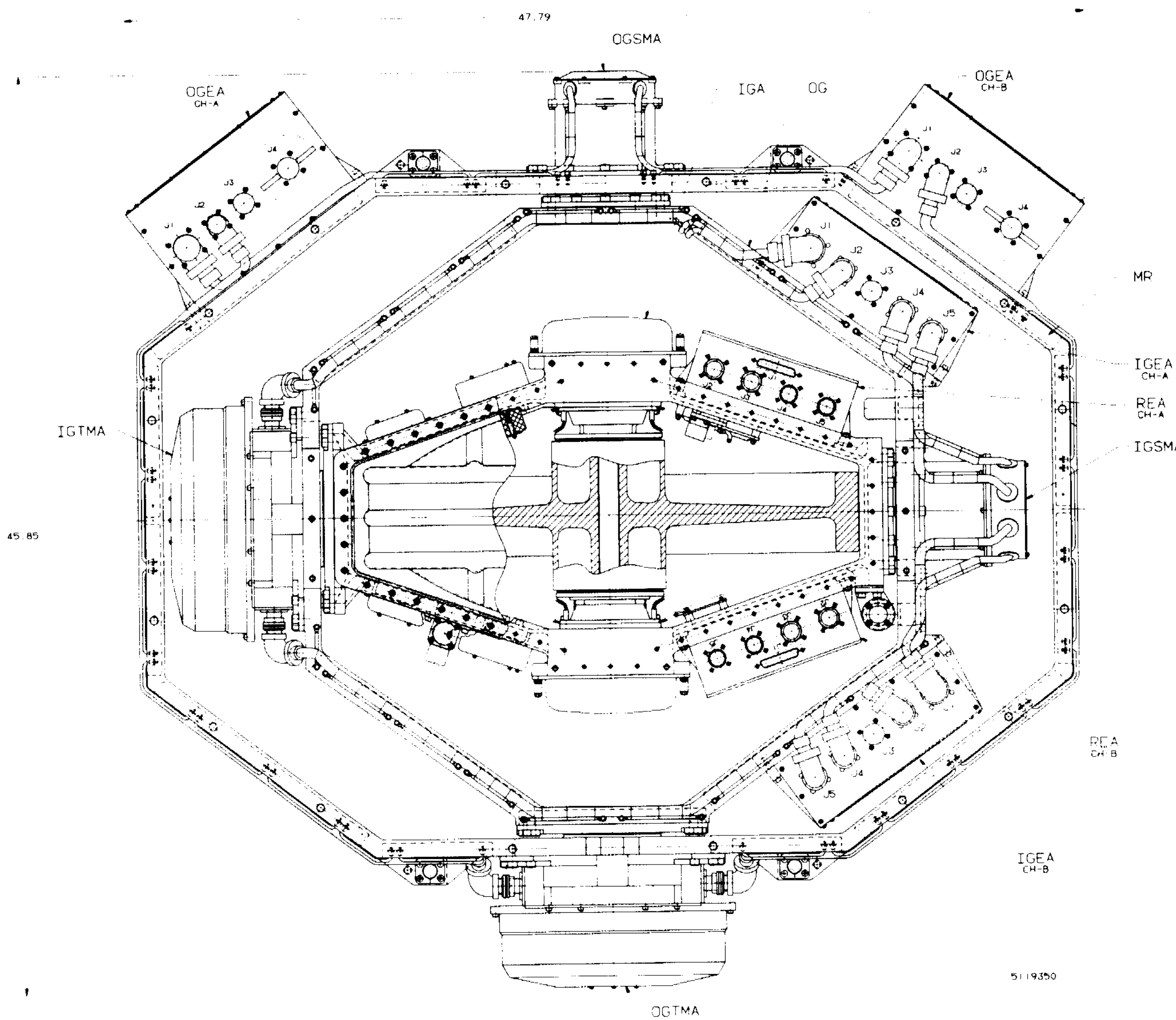

Figure 1. Layout of prototype DGCMG system.

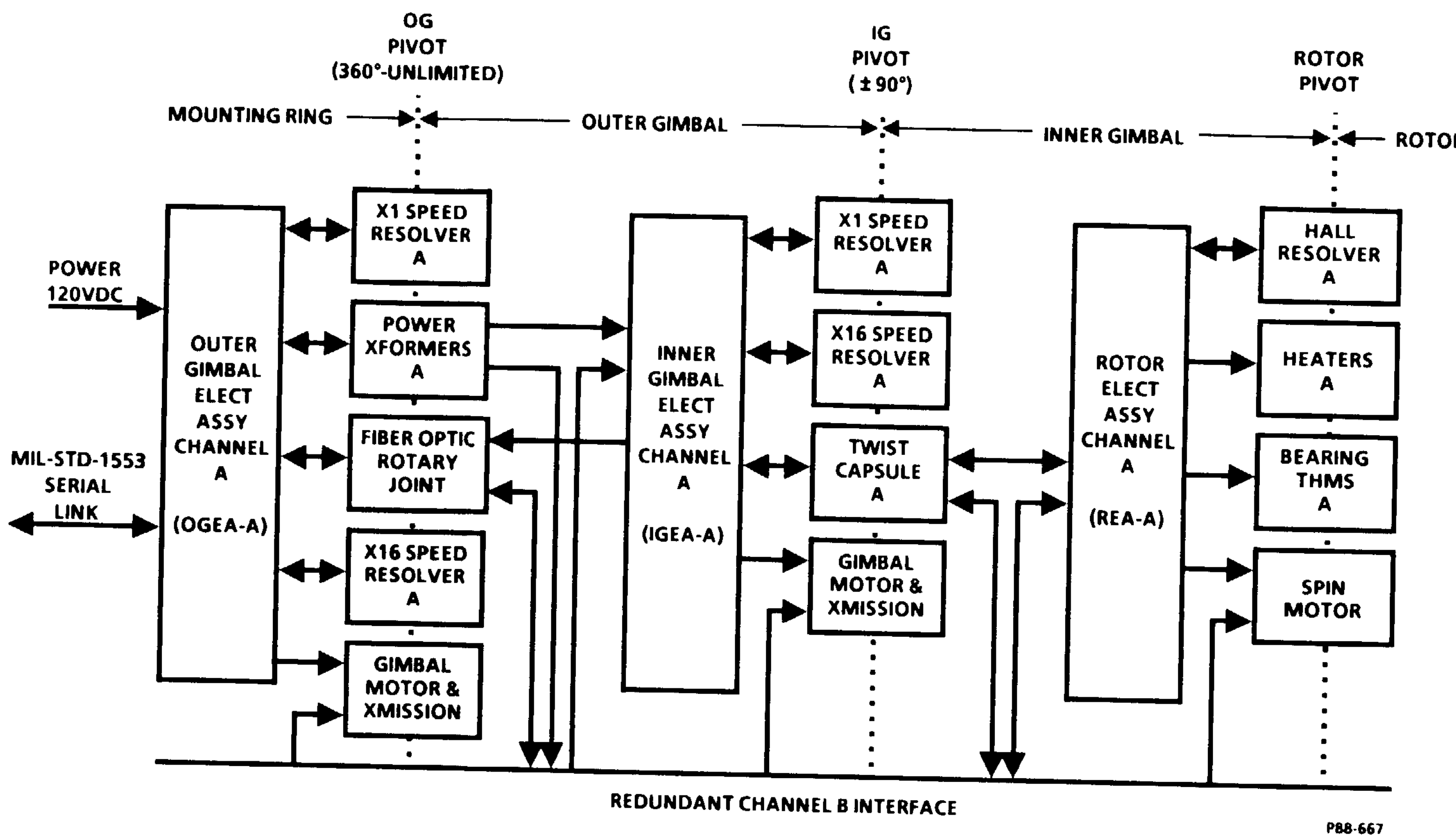

Figure 2. System block diagram.

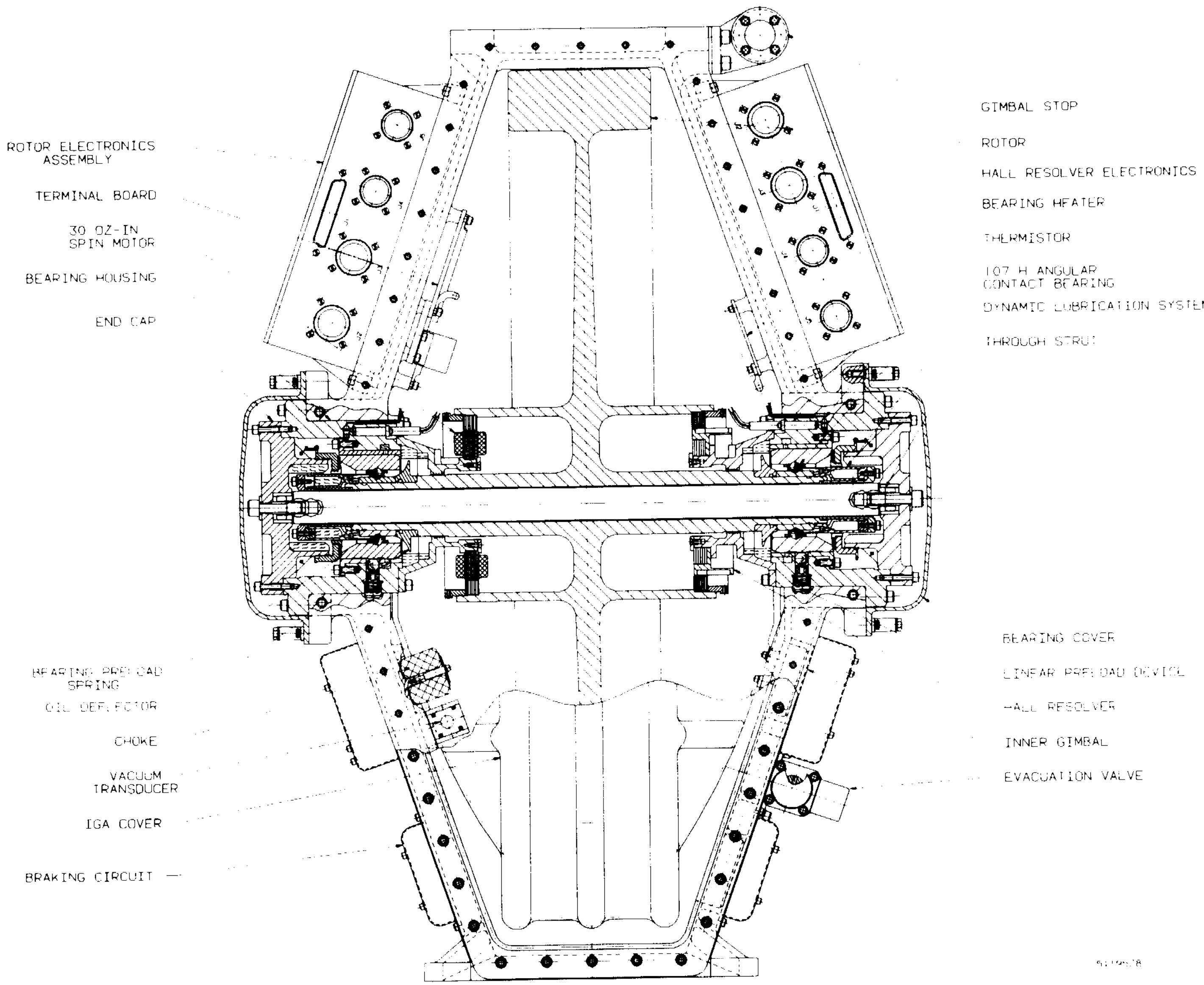

Figure 3. Inner gimbal assembly.

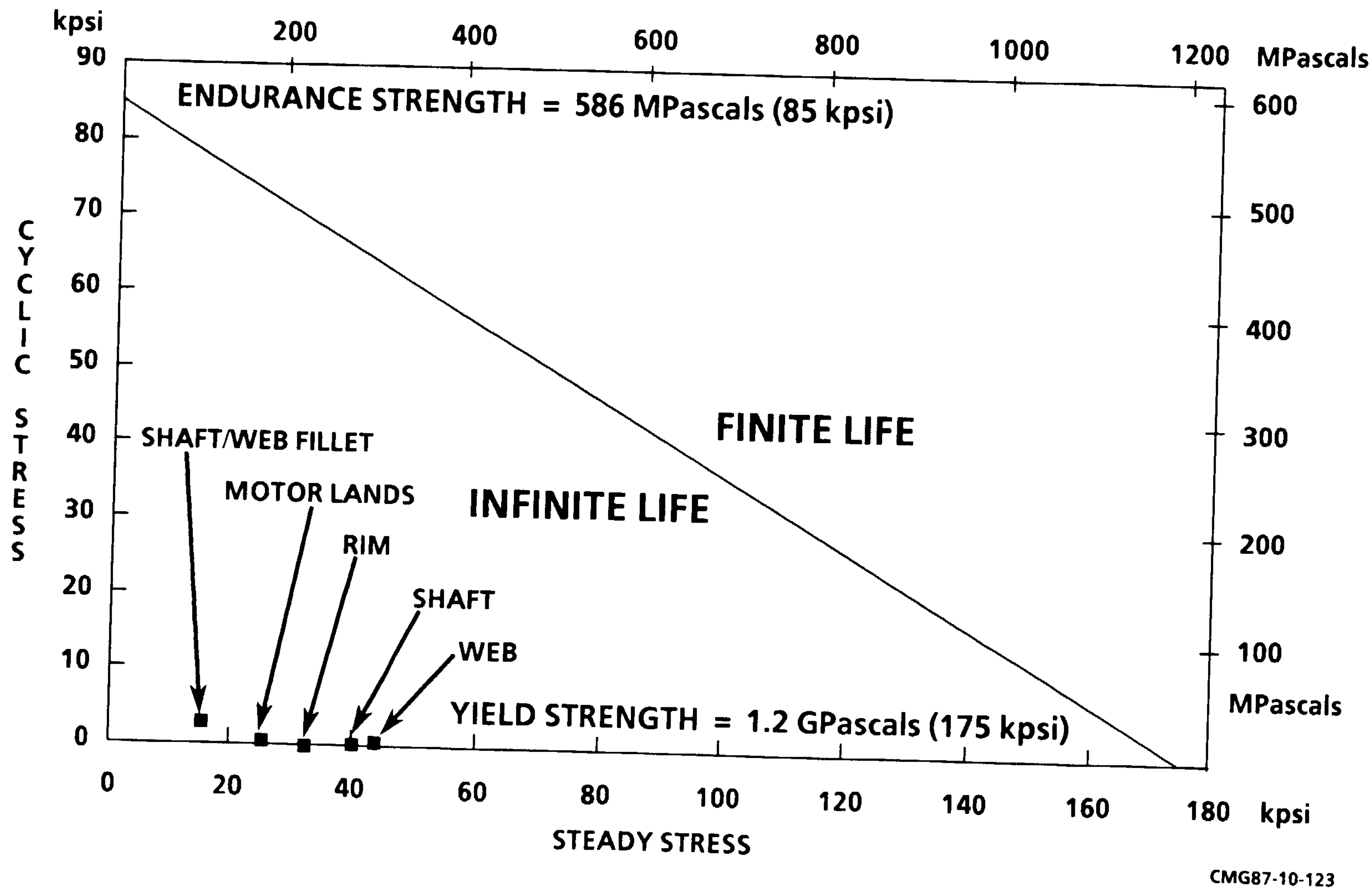

Figure 4. Modified Goodman diagram of rotor stresses.

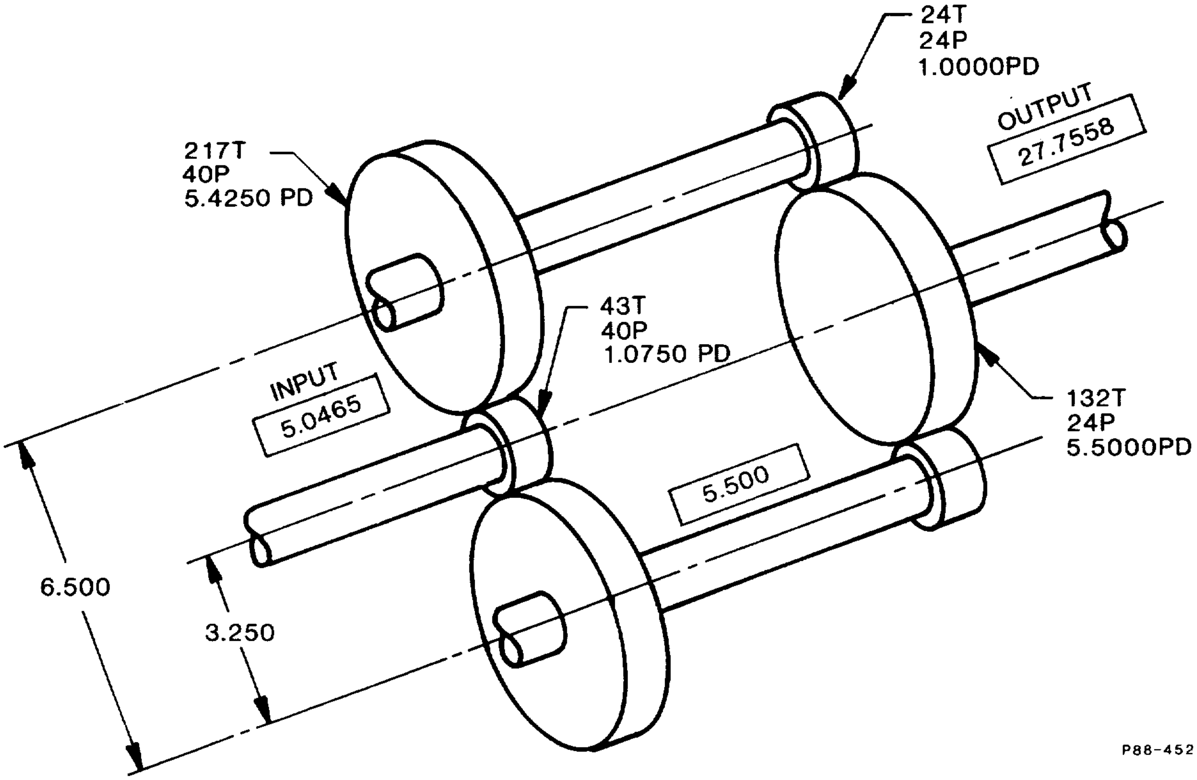

Figure 5. Parallel path gear train transmission.

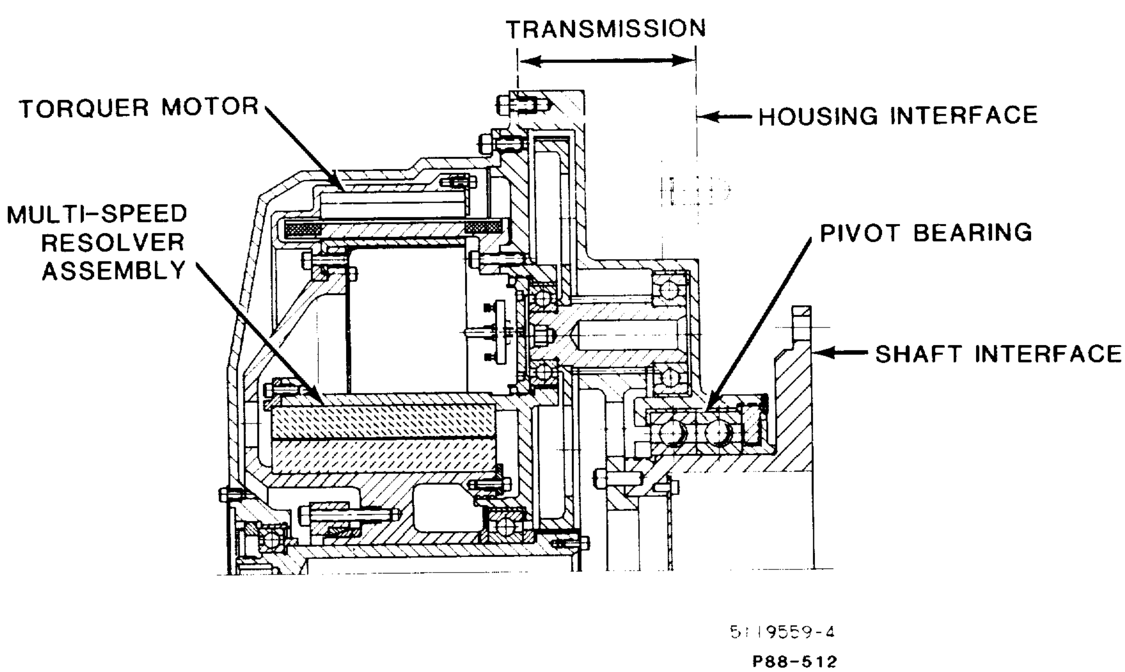

Figure 6. Torquer module assembly cross-section.

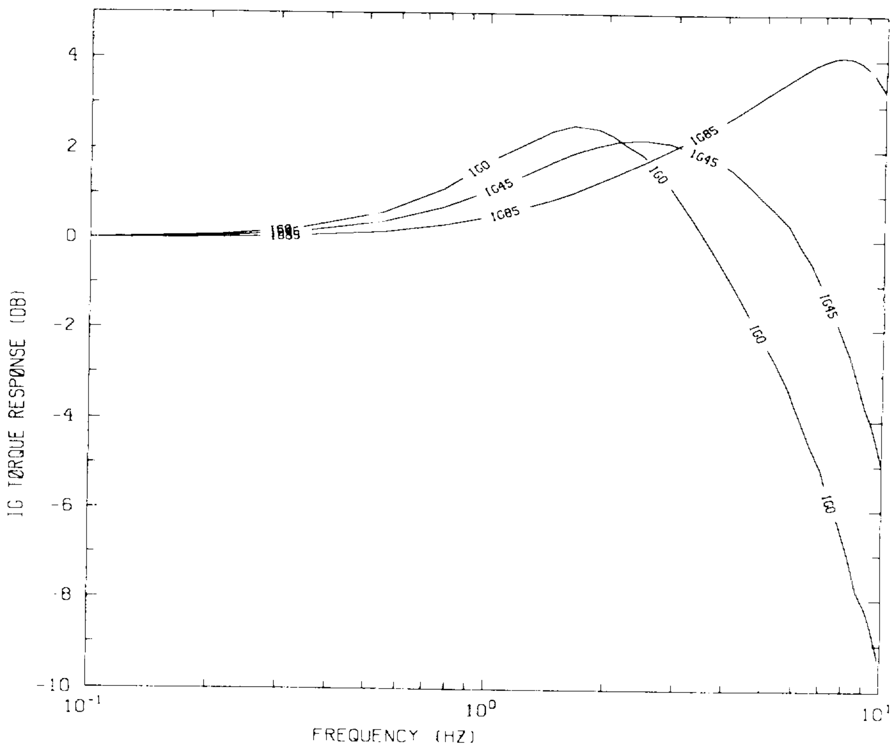

Figure 7. Math model prediction of IG loop frequency response.

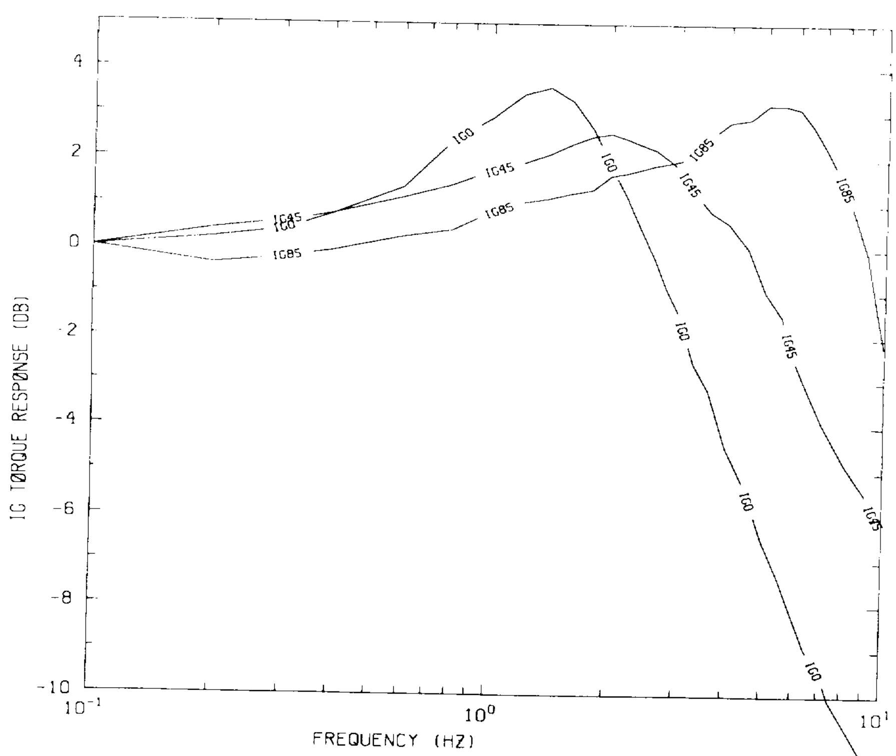

Figure 8. Measured IG loop frequency response.

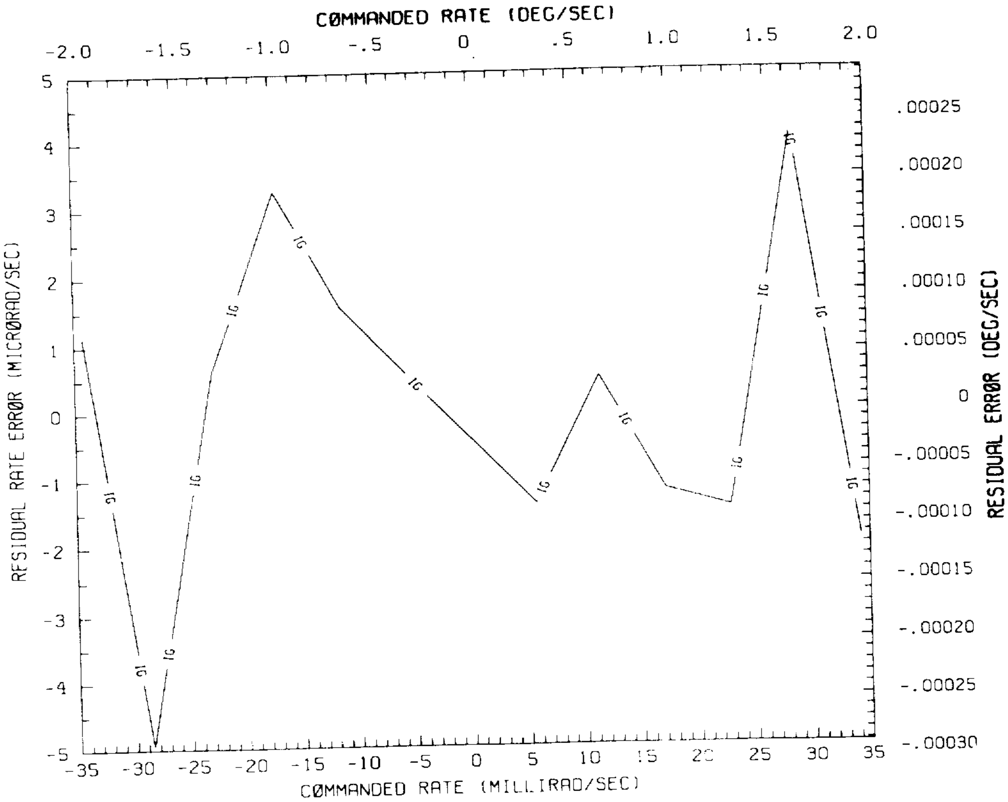

Figure 9. Inner gimbal loop linearity performance.

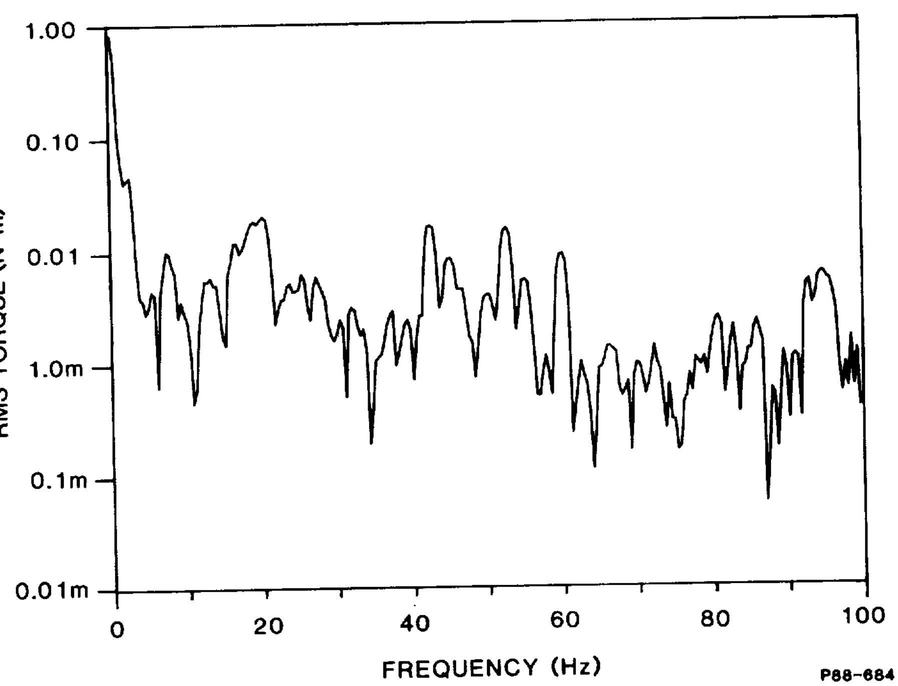

Figure 10. Torque noise performance.